The kilonova AT2017gfo was spherically symmetric

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Abstract

During the merger of neutron stars, radioactive matter is liberated, yielding a luminous optical transient, called a kilonova[1,2]. The first, and so-far only, well-studied kilonova was AT2017gfo[3,4,5,6], discovered after follow-up[7] of the neutron-star–merger gravitational wave event, GW170817[8]. Little is known observationally about the overall geometry of the merger's ejecta which is strongly dependent on the neutron stars' mass ratio and equation of state. Hydrodynamical merger models typically show axisymmetric, strongly aspherical ejecta[9,10,11]. We show here that we can make highly accurate measurements of AT2017gfo's radial-to-tangential asymmetry by comparing the velocity of the absorption lines of Sr^{+} to the inferred blackbody size at the time of the spectroscopic observations. Contrary to current models, which show a range of aspherical geometries, the kilonova is extremely close to spherical, with an asymmetry index $\boldsymbol{\Upsilon = 0.00 \pm 0.03}$ assuming $\boldsymbol{H_0 = 67.3 \pm 0.5}$[12], with the dominant uncertainty being the cosmological distance to the host galaxy[12,13,14]. Considering the large range of model predictions it is hard to explain the fine-tuned sphericity in current hydrodynamic merger models. Strong heating of the

ejecta could drive the kilonova toward sphericity, possibly requiring more thermal energy than is available from radioactive heating. Additional energy could be provided by a short-lived millisecond magnetar [15] or magnetic heating from collapse of the supermassive neutron star remnant to a black hole [16]. Such sphericity also places strong demands on the initial ejecta distribution and hence on the neutron star equation of state. Finally, the highly spherical ejecta means that kilonovae can be used to measure precise cosmological distances; AT2017gfo is determined to be at $\mathbf{43.22 \pm 0.36}$ Mpc, with a precision of better than 1%.

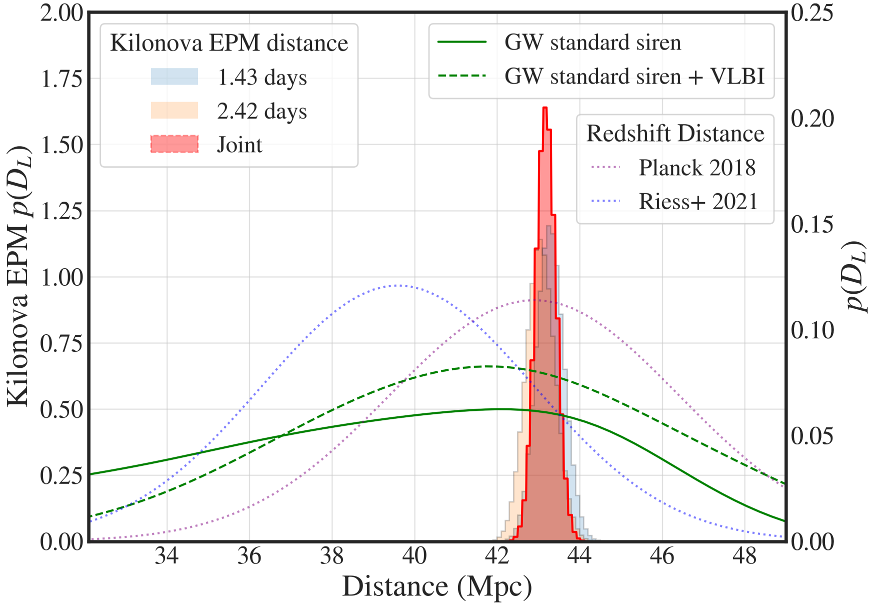

Fig. 1 **Probability distributions of the luminosity distance to the kilonova AT2017gfo.** Our distance estimates based on the kilonova expanding photospheres method for the spectra obtained at 1.43 and 2.42 days and their combined constraint are shown as filled blue, salmon, and red histograms respectively. The gravitational wave standard siren distance estimate with and without very long baseline interferometry radio data are shown as dashed and solid green lines respectively. Cosmological redshift distances assuming $H_0 = 67.36 \pm 0.54$ [12] (dotted purple) and $H_0 = 73.03 \pm 1.04$ [13] (dotted blue).

References

1. Barnes J, Kasen D (2013) Effect of a High Opacity on the Light Curves of Radioactively Powered Transients from Compact Object Mergers. 775(1):18. https://doi.org/10.1088/0004-637X/775/1/18, https://arxiv.org/abs/arXiv:1303.5787 [astro-ph.HE]

2. Tanvir NR, Levan AJ, Fruchter AS, et al (2013) A ‘kilonova’ associated with the short-duration γ-ray burst GRB 130603B. 500(7464):547–549. https://doi.org/10.1038/nature12505, https://arxiv.org/abs/arXiv:1306.4971 [astro-ph.HE]

3. Coulter DA, Foley RJ, Kilpatrick CD, et al (2017) Swope Supernova Survey 2017a (SSS17a), the optical counterpart to a gravitational wave source. Science 358(6370):1556–1558. https://doi.org/10.1126/science.aap9811, https://arxiv.org/abs/arXiv:1710.05452 [astro-ph.HE]

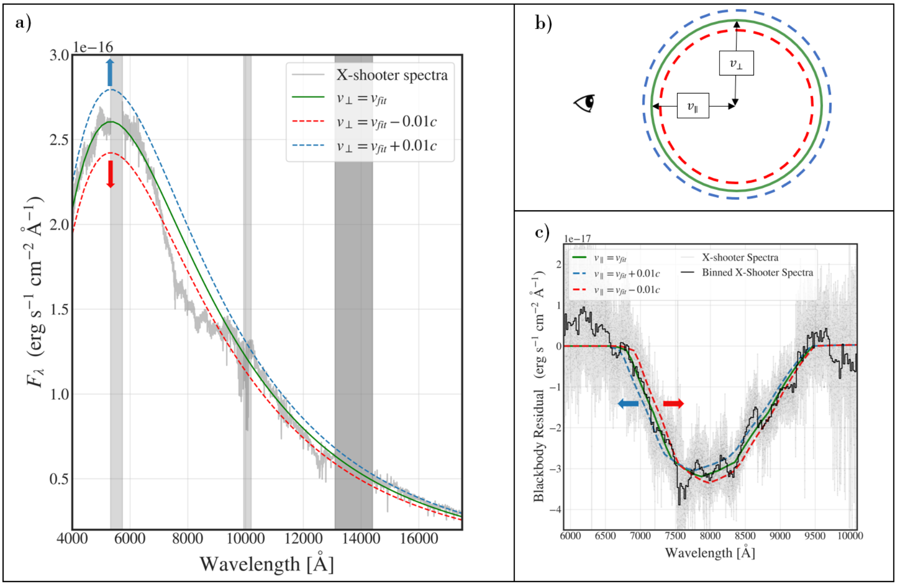

Fig. 2 Illustration of the expanding photospheres method for the kilonova AT2017gfo. a) 1st Epoch X-shooter spectrum with overlayed blackbody fits. The normalisation for each blackbody is set by the cross sectional radius, which requires an a-priori distance (here assuming Planck cosmology) and cross-sectional velocity, $v_\perp$. $v_\perp$ is illustrated for smaller (dashed red), equal (green line) or greater (dashed blue) than the best-fit velocity, v_{fit}. b) Illustration of $v_\parallel$ and $v_\perp$ which are respectively set by the P Cygni absorption feature and the blackbody normalisation. c) Cutout of Sr II absorption component from 1st epoch with blackbody continuum fit subtracted from X-shooter spectrum. Overlayed is P Cygni profile given $v_\parallel$ is smaller (dashed red), equal (green line) or greater (dashed blue) than $v_{\rm fit}$. Ultimately, the continuum and absorption line yield velocities in tight agreement.

4. Drout MR, Piro AL, Shappee BJ, et al (2017) Light curves of the neutron star merger GW170817/SSS17a: Implications for r-process nucleosynthesis. Science 358(6370):1570–1574. https://doi.org/10.1126/science.aaq0049, https://arxiv.org/abs/arXiv:1710.05443 [astro-ph.HE]

5. Pian E, D'Avanzo P, Benetti S, et al (2017) Spectroscopic identification of r-process nucleosynthesis in a double neutron-star merger. 551(7678):67–70. https://doi.org/10.1038/nature24298, https://arxiv.org/abs/arXiv:1710.05858 [astro-ph.HE]

6. Smartt SJ, Chen TW, Jerkstrand A, et al (2017) A kilonova as the electromagnetic counterpart to a gravitational-wave source. 551(7678):75–79. https://doi.org/10.1038/nature24303, https://arxiv.org/abs/arXiv:1710.05841 [astro-ph.HE]

7. Abbott BP, Abbott R, Abbott TD, et al (2017) Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A. 848(2):L13. https://doi.org/10.3847/2041-8213/aa920c, https://arxiv.org/abs/arXiv:1710.05834 [astro-ph.HE]

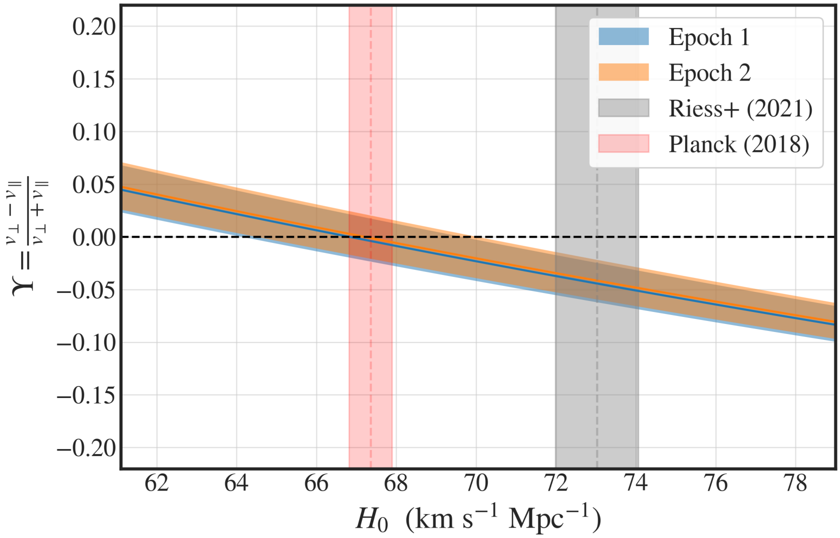

Fig. 3 **Asymmetry index for 1st and 2nd epoch as a function of** H_0. There exists a complete degeneracy between Υ and H_0, with higher H_0 yielding increasingly prolate ejecta. Both early- and late-estimates of H_0 suggests expansion is close to symmetric, with less than 10% variation between the velocities.

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8. Abbott BP, Abbott R, Abbott TD, et al (2017) A gravitational-wave standard siren measurement of the Hubble constant. 551(7678):85–88. https://doi.org/10.1038/nature24471, https://arxiv.org/abs/arXiv:1710.05835 [astro-ph.CO]

9. Hotokezaka K, Kiuchi K, Kyutoku K, et al (2013) Mass ejection from the merger of binary neutron stars. 87(2):024001. https://doi.org/10.1103/PhysRevD.87.024001, https://arxiv.org/abs/arXiv:1212.0905 [astro-ph.HE]

10. Bauswein A, Goriely S, Janka HT (2013) Systematics of Dynamical Mass Ejection, Nucleosynthesis, and Radioactively Powered Electromagnetic Signals from Neutron-star Mergers. 773(1):78. https://doi.org/10.1088/0004-637X/773/1/78, https://arxiv.org/abs/arXiv:1302.6530 [astro-ph.SR]

11. Rosswog S, Korobkin O, Arcones A, et al (2014) The long-term evolution of neutron star merger remnants - I. The impact of r-process nucleosynthesis. 439(1):744–756. https://doi.org/10.1093/mnras/stt2502, https://arxiv.org/abs/arXiv:1307.2939 [astro-ph.HE]

12. Aghanim N, Akrami Y, Ashdown M, et al (2018) Planck 2018 results. VI. Cosmological parameters. arXiv e-prints arXiv:1807.06209. https://arxiv.org/abs/arXiv:1807.06209 [astro-ph.CO]

13. Riess AG, Yuan W, Macri LM, et al (2021) A Comprehensive Measurement of

the Local Value of the Hubble Constant with 1 km/s/Mpc Uncertainty from the Hubble Space Telescope and the SH0ES Team. arXiv e-prints arXiv:2112.04510. https://arxiv.org/abs/arXiv:2112.04510 [astro-ph.CO]

14. Mukherjee S, Lavaux G, Bouchet FR, et al (2021) Velocity correction for Hubble constant measurements from standard sirens. 646:A65. https://doi.org/10.1051/0004-6361/201936724, https://arxiv.org/abs/arXiv:1909.08627 [astro-ph.CO]

15. Metzger BD, Piro AL (2014) Optical and X-ray emission from stable millisecond magnetars formed from the merger of binary neutron stars. 439(4):3916–3930. https://doi.org/10.1093/mnras/stu247, https://arxiv.org/abs/arXiv:1311.1519 [astro-ph.HE]

16. Nathanail A (2018) An Explosion is Triggered by the Late Collapse of the Compact Remnant from a Neutron Star Merger. 864(1):4. https://doi.org/10.3847/1538-4357/aad3b8, https://arxiv.org/abs/arXiv:1801.05680 [astro-ph.HE]